

FEATURES

FRONTLINE SCIENCE



As Ukraine's war with Russia grinds on, the nation's civilian scientists are playing a growing role in military R&D

RICHARD STONE,
in Kyiv and Dnipro, Ukraine

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On a recent Saturday afternoon, Bohdan, a 26-year-old engineer, roused an attendant to unlock the door to a science building in a secluded corner of Kyiv Polytechnic University (KPU). Rail-thin and intense, Bohdan, who did not reveal his last name to protect himself and his father, an artillery officer in the Ukrainian army, bounded down concrete steps to a basement workshop. There, under a Soviet-style poster urging “To the Occupier, Invader, Looter, Murderer: Death!” a KPU physics student was hunched over a circuit board. Bohdan’s team was racing to finish a new iteration of a drone it had promised to deliver to the military that June evening.

They had started with a DJI Mavic 3 quadcopter, a Chinese-made machine about 30 centimeters from rotor to rotor, available on the internet for about \$2000. “This is a crucial instrument for reconnaissance and targeting,” Bohdan explained. He and his grad students had already doubled the drone’s maximum flight time to

80 minutes. Now, they were testing a hidden enhancement to their Kruk, or Raven, drone: a communications link that resists jamming. “The electronic warfare environment is getting extremely complicated. The Russians blast everything up to 15 kilometers in front of them,” Bohdan said.

The KPU team is just one of a legion of academic research groups that Ukraine, now in its fourth year of grinding warfare with Russia, has mobilized in hopes of achieving a technological edge over its much larger and better armed enemy. With Russian forces having repeatedly targeted the nation’s military R&D centers, the government has pressed wide swaths of Ukraine’s civilian science infrastructure into service to conduct military research. “We had to change our priorities to defense and security. Many institutes are rather deeply involved now,” says Anatoly Zagorodny, president of the National Academy of Sciences of Ukraine (NASU). Bohdan, for one, calls it his “ideological obligation” to develop killer drones. “There are



Smoke rises after a Russian drone and missile attack on Kyiv, Ukraine, on 4 July.

the front lines, in Kyiv and other places where universities and research institutes are located. The attacks, often occurring in the middle of the night, are growing deadlier and inflicting a rising toll on the mental health of soldiers and civilians alike.

"I'm psychologically traumatized, 100%," Polotska says. "It is getting very difficult to hold on."

THE CHIEF ARCHITECT of the full-court research effort is Volodymyr Horbulin, an 86-year-old veteran of Ukraine's rocket and space industry. During the Cold War, Horbulin was part of an R&D team at Yuzhmash, a Ukrainian aerospace factory that produced Kosmos rockets for the Soviet Union. (In the past 3 years Russia has repeatedly targeted the facility, now known as Pivdenmash.) After Ukraine gained its independence in 1991, he headed its nascent National Space Agency. Then in 2015, the year after fighting broke out in Donbas, Horbulin became the first vice president of NASU and spearheaded an initial slate of defense science projects.

Meager resources frustrated Horbulin, who decried a lack of political will to develop key defense technologies. In a prophetic 2020 book, *How to Defeat Russia in a Future War*, he flagged the importance of uncrewed aerial vehicles (UAVs), pointing to a drone attack on a Saudi oil refinery in 2019 that halved the nation's total production for days. Declaring that the 2020s would be "the most dangerous and unpredictable" decade for modern Ukraine, Horbulin called for national programs on UAVs, high-precision weapons, and electronic warfare systems.

The COVID-19 pandemic slowed those ambitions. But Russia's full-scale invasion in 2022 brought new urgency to government efforts to expand military R&D. Since then, Horbulin has forged close ties with Ukraine's defense establishment to tailor NASU's research pipeline to the military's needs. One recent example is an agreement with Defence Intelligence of Ukraine (DIU) under which NASU institutes will develop UAVs and satellite systems. "No matter how difficult it may be, we must support and develop our science, as it is of fundamental importance for the defense of Ukraine," DIU Chief Kyrylo Budanov said after

meeting Horbulin and Zagorodny in December 2024.

Horbulin's focus on drones seemed especially prescient on the morning of 17 June, when the air in downtown Kyiv was thick with an acrid, burnt smell. Gray smoke clung to rooftops in a southern district of Ukraine's capital, where a Russian missile had slammed into an apartment building early that morning. A drone also struck a dormitory at the Kyiv Aviation Institute, a university hotbed for drone R&D. All told, Ukrainian officials said Russia overnight had launched 440 drones and 32 missiles at Kyiv, killing 30 and injuring 172.

"I didn't sleep at all," confessed Maksym Iurzhenko, a materials scientist at the E.O. Paton Electric Welding Institute (PWI), one of several dozen NASU institutes involved in Horbulin's military R&D campaign. Iurzhenko's family members had spent the night in their apartment complex's basement for the third time in a week. His 7-year-old daughter has been having a particularly rough time, he says. "It's impossible to feel safe."

PWI is a behemoth: Its labs, staffed by a 500-strong scientific corps, take up a city block, and it has design shops and factories elsewhere. The facilities have become obvious targets for Russian forces and "have suffered from attacks, some severely," Iurzhenko says.

Visitors to PWI are greeted by a Soviet-era example of its applied handiwork: a segment of natural gas pipeline, the length and height of a tractor trailer, engineered to limit the damage from explosive accidents. To diversify PWI's research, in 2014 the institute recruited Iurzhenko to head a new department of plastic welding. That year, Russia seized Crimea from Ukraine and Russian-backed separatists rose up in the eastern Donbas region. Iurzhenko's team soon got its first request from the Ukrainian military: to develop an inflatable sleeve made from welded plastic that battlefield medics could use to immobilize wounded appendages before transporting casualties to a hospital. Scores are now in use.

In recent months, PWI's defense R&D portfolio has been booming. Iurzhenko could shine a spotlight on two projects. One is aimed at developing a 3D-printed biopolymer implant for repairing bone breaks. The implant would dissolve as new bone forms, eliminating the need for, say, a titanium implant that would later

“We had to change our priorities to defense and security.”

Anatoly Zagorodny
National Academy
of Sciences of Ukraine

predators, and there are victims. We don't want to be the victim."

The work extends far beyond drone innovation. It includes projects on multispectral mobile camouflage, directed-energy weapons, and glass ceramics for rockets—all closely guarded secrets. "There are some absolutely amazing projects that we can talk about only after the war ends," says Olga Polotska, executive director of the National Research Foundation of Ukraine (NRFU). But Ukrainian scientists recently agreed to lift the veil on some other research efforts for *Science*, allowing a reporter to observe work in an array of areas, including sea drones, military medicine, and technology for safeguarding critical infrastructure and iconic historic buildings.

The war is touching many researchers personally as well as professionally, as bombardments escalate well behind

be removed surgically. The team has completed safety testing and is starting trials in wounded soldiers.

PWI is also one of several NASU institutes developing gel bandages infused with medicines. Iurzhenko's team has concocted two formulations: one with microbicidal nanoparticles of silver, and a second with zinc oxide and other compounds that promote tissue regeneration. Both are being tested in hospitals. Another gel in development across town at the Institute for Molecular Biology and Genetics taps into the healing powers of kombucha, a fermented beverage with bacteria and yeast.

Other teams are cooking up wound-healing ointments. One intriguing concoction is a medley of kaolin and silica to stop bleeding, along with silver and gold nanoparticles and unripe walnuts. The walnut extract and the precious metals reduce inflammation and kill microbes, says Ihor Zatovsky, a chemist at NASU's F.D. Ovcharenko Institute of Biocolloidal Chemistry. One goal is to thwart the dangerous strains of antibiotic-resistant bacteria circulating in Ukrainian soldiers (*Science*, 6 December 2024, p. 1085). Hospital trials are expected to start soon.

A CELEBRATED ATTACK carried out by Ukraine 3 years ago has inspired aerospace expert Andrii Dreus to try to resurrect, in miniature form, a Soviet-era fever dream known as the Caspian Sea Monster. The October 2022 attack used a truck bomb to collapse a

section of the Kerch Bridge connecting Russia and Crimea. Ukrainians welcomed the assault on the bridge, which Russia completed in 2018 at a cost of \$3.7 billion and has been using to supply troops.

The bold blow stirred Dreus, a specialist in fluid mechanics at Oles Honchar Dnipro University in southeastern Ukraine, to ponder new ways to attack over water. He turned to an aerodynamic phenomenon that Soviet engineers explored during the Cold War called the ground effect: the air cushion that builds up between a low-flying aircraft and the ground, increasing lift and reducing drag. "Ekranoplans" can in theory carry more weight at higher speeds than conventional aircraft, and by flying low they can avoid radar detection.

The Soviet *pièce de résistance* was the Korabl Maket (KM), an ekranoplan with 10 turbojet engines and a wingspan of nearly 38 meters that flew at an altitude of just several meters. Completed in 1966, the KM was then the largest aircraft ever built and reportedly could attain speeds of 650 kilometers per hour. The Soviet navy spent 15 years testing the craft on the Caspian before it crashed and sank in 1980; other Soviet ekranoplans operated into the 1990s. (Earlier this month, news outlets reported that China has begun to test its own ekranoplan—nicknamed the Bohai Sea Monster—on the Bohai Sea.)

As a student at the university, located in Dnipro—a closed city in Soviet

days because of its military industries—Dreus had completed an aerodynamics assignment on ekranoplans. He knew they could be capricious. The smaller the ekranoplan, the more its stability is perturbed by uneven topography, which on open water means waves. Dreus's university has one of Ukraine's few operational wind tunnels, which he and his team used to test a variety of designs. They hit on a winner: a drone with a 6-meter wingspan that should fly at 250 kilometers per hour. They recently presented their concept to the Ministry of Strategic Industries of Ukraine and are huddling with private companies on building a prototype, Dreus says.

An ekranodrone would add to Ukraine's mushrooming arsenal of UAVs, which on 1 June starred in one of the military's most audacious maneuvers: Operation Spiderweb. It used fake cargo containers to smuggle drones into Russia by truck months before the attack, then unleashed them on military aircraft at bases deep inside the country. "It was the culmination of a new tactic: bringing a strike capability closer to a target," says Kateryna Bondar, a defense analyst at the Center for Strategic and International Studies.

Most common on the Ukrainian front lines is a first-person view (FPV) drone: typically, a camera-equipped quadcopter that a remote operator controls using goggles. This year, Ukraine has vowed to churn out 4.5 million FPV drones, which can



A nighttime drone strike on a Kyiv, Ukraine, apartment building forced residents into the street on 10 July.

Caught in the crosshairs

In the child's drawing, a blue-and-yellow umbrella the size of a city block shields homes and apartments from fighter jets screaming toward Dnipro, an industrial city in southeastern Ukraine that Russia has hit hard and often during the war. *Ukraine Wants Peace!* the elementary school artist titled the work, an entry in a competition staged earlier this year by the M.S. Poliakov Institute of Geotechnical Mechanics for families of its staff. "This is a small way to help people cope. To relieve the terrible stress we are all under," says Anatoly Bulat, the institute's director.

After years of daily air raid alerts and predawn fusillades of drones and missiles that disrupt sleep and stoke anxiety, malaise is rampant across Ukraine. "I feel like my youth is being stolen. What should be the best time of my life," says Oleksandra Kyselova, a 24-year-old legal expert at the National Research Foundation of Ukraine (NRFU) in Kyiv. She says she has become so inured that, despite the obvious danger, she no longer seeks shelter during attacks. "Not all wounds are visible," says Oksana Mankovska, a molecular biologist at the Institute of Molecular Biology and Genetics (IMBG).

As Ukraine's scientific establishment pivots toward war-related work (see main story, p. 446), the war's mental health burden is one major

be fitted with diverse weaponry or used for reconnaissance. Other UAVs include larger missile-launching drones, Baba Yaga night-strike drones adapted from agricultural drones that spray crops, and interceptors used with increasing success to take out Russia's long-range Geran drones. Ukraine also has a menagerie of boat drones as well as uncrewed ground vehicles for laying mines, demining, and kamikaze missions.

Ukraine has been particularly adept at militarizing commercial technology. For instance, Bondar says, developers have devised software for autonomous navigation that makes off-the-shelf FPV drones several times more likely to hit their targets. "You need fewer drones this way," she says. And anyone with access to a 3D printer can pitch in to the war effort. A nonprofit, 3D Print Army, passes along requests from Ukraine's military to volunteers across Europe. "People print little parts and pieces the army needs," such as a bomb-release element attached to Baba Yaga drones, Bondar says. Since the start of the full-scale invasion, 3D Print Army says it has delivered more than 18 million items to the front lines.

Ukraine is up against Russia's own formidable drone capabilities. Night after night, Russia unleashes waves of Geran drones with 2.5-meter wingspans, modeled after the Iranian Shahed drone. And Russia had a huge advantage at the outset of the full-scale invasion: unrivaled

expertise in electronic warfare, used to jam and disable Ukrainian drones. "Ukraine realized that there is no point in competing with Russia in electronic warfare. They're the best in the world," Bondar says.

Instead, Ukraine has honed asymmetric responses. For instance, scientists at NASU institutes and at universities are developing artificial intelligence systems for their drones that analyze which frequencies Russians are jamming and quickly shift communications links to a viable frequency. "It's a cat-and-mouse game," Bondar says. Another clever countermeasure is a wristwatch developed at Lviv Polytechnic National University that detects the sounds of an incoming drone long before soldiers hear them, then broadcasts an alert via Bluetooth to comrades nearby. Other countermeasures are decidedly low-tech. For example, Ukrainian soldiers have on occasion disabled sophisticated Russian drones connected to operators via fiber optic cables by snipping the cable with kitchen shears.

The drone arms race is redefining the art of war in ways that other nations, including China and the United States, are only beginning to fathom. "Now, governments have to think that basically anything can be militarized in a garage or basement," Bondar says. "You don't know how it's going to be used, when and where it's going to be deployed, and how to counter the threat."

ON 12 DECEMBER 2023, Russia carried out a devastating cyberattack on Ukraine's biggest mobile network operator, Kyivstar. The 2-week outage affected 24 million people; hobbled military, energy, banking, and transportation communications; and disabled a nationwide air raid warning system. To prevent a similar future attack from silencing cellular communications, Mykola Beshley, an information technologies specialist at Lviv Polytechnic, devised an intelligent system to divert cellular calls to Wi-Fi and the internet. The technological and software tweaks now enable stable calls over Ukrainian Wi-Fi networks if the cell signal is lost.

Russia also regularly resorts to brute force—missiles and mortars—to degrade Ukraine's critical infrastructure, with power stations and substations a frequent target. Those attacks have stimulated a groundswell of R&D on fortifying the electrical grid. One simple solution is a shipping container-size module filled with heavy-duty vehicle batteries that can be deployed to critical facilities. In the event of a power outage, the 50-kilowatt unit instantly supplies electricity for essential needs such as hospital life support equipment. The unit can run for hours—or even days if it is recharged by solar panels or wind turbines, says Dmytro Redchys, director of NASU's Institute of Transport Systems and Technologies, which is building the units. "This is

“We’re staying here, doing our research. That’s how we are fighting for our liberty.”

Maksym Iurzhenko
E.O. Paton Electric
Welding Institute

focus. Later this year NRFU, with support from the Research Council of Norway, will call for proposals for mental health studies that would likely cover all segments of society, from soldiers on the front lines to civilians taking refuge in havens in western Ukraine, far from the fighting. "Sadly, Ukraine has become a huge field for this research," says Olga Polotska, NRFU's executive director.

One obvious research target is post-traumatic stress disorder (PTSD), a malady with symptoms including mood changes, flashbacks, and insomnia. The Ukrainian military does not release statistics on PTSD incidence among soldiers. But rates in the civilian population appear to be formidable. In 2024, online survey results published in *The Lancet* reported PTSD levels of 47% among civilians (mostly women and children) who had fled the country, 33% of those who were internally displaced, and 39% of those remained in their homes.

Because PTSD's psychological symptoms can vary, researchers have also sought verified biological markers, such as elevated levels of certain blood compounds. To make headway, a team led by Mankovska is studying soldiers at a rehabilitation center near Kyiv diagnosed with PTSD, PTSD plus traumatic brain injury, and complex PTSD (CPTSD), a more severe form that can develop after chronic exposure to trauma.

Because PTSD is sometimes associated with autoimmune condi-

tions such as inflammatory bowel disease, rheumatoid arthritis, and dermatitis, the scientists are keying in on cytokines: signaling proteins that trigger and regulate immune responses. They are sending serum samples from ill soldiers and controls to Holden Maecker, an immunologist at Stanford University, to test for the presence of up to 250 cytokines. Researchers think it "unlikely that there would be one or a few cytokines that would totally discriminate between PTSD and non-PTSD," Maecker says. But one hope, he says, is that the Ukrainian team will find "a constellation of cytokines" linked to PTSD.

Working with molecular biologist Victor Dosenko of the Bogomoletz Institute of Physiology, Mankovska's team has found that PTSD and CPTSD patients appear to have distinct patterns of DNA methylation, in which methyl groups added to DNA turn genes on or off. "We have found very high levels of methylation" in afflicted soldiers, which could promote accelerated biological aging and other telltale effects, says IMBG's Leonid Shevchenko.

They are also exploring whether exosomes—vesicles that ferry proteins, RNA, and other molecules between cells—carry immune-related molecules heralding PTSD. "We need to dive deeper," Mankovska says. Unfortunately, there is no shortage of PTSD sufferers in Ukraine for their research. —R.S.



Ukrainian soldiers launch a Baba Yaga drone, which excels at nighttime strikes, in the Zaporizhzhia region (above); a comrade pilots a first-person view (FPV) drone (right) in the Kharkiv region. Ukraine has vowed to make 4.5 million FPV drones this year.



many times cheaper than using a diesel generator, and has zero CO₂ emissions,” he says. But in the early morning hours of 26 July, Russia hit the factory producing the battery unit with drones and Iskander ballistic missiles, destroying much of its unique equipment, Redchits says. “Fortunately, all the plant workers survived,” he says.

Ukraine’s cultural heritage is also at risk. In the early morning of 10 June, a blast wave from a nearby strike damaged the façade of St. Sophia Cathedral, the 11th century UNESCO World Heritage Site in Kyiv. Ukrainian President Volodymyr Zelenskiy decried the attack as “unacceptable and catastrophic.”

Fortunately, the damage to St. Sophia was superficial, says Stella Shekhunova, director of NASU’s Institute of Geological Sciences (IGS). But it can take time for the damage caused by blast waves to reveal itself, as cracks expand and disturbed soils settle beneath foundations. To get advance warning of such structural threats, Shekhunova’s staff has installed accelerometers, velocimeters, and other upgraded monitoring equipment at another of Ukraine’s cultural treasures: the sprawling Kyiv-Pechersk Lavra, a monastery with a labyrinth of catacombs that monks first inhabited in the 11th century.

Perched above the Dnipro River, the World Heritage Site straddles a slope composed of loess, sand, and clay. As a result, the ground beneath many of its historical buildings—including a pair of imposing centerpieces, the Great Lavra Bell Tower and the Dormition Cathedral—is exquisitely vulnerable to shaking. Over the centuries, the Lavra’s keepers have built retaining walls to shore it up.

IGS’s monitoring system has documented cracks that appeared in the Lavra’s walls after Ukraine shot down missiles or drones five or more kilometers from the monastery. So far, it has dodged serious damage, Shekhunova says. But a strike within a few kilometers—not to mention a direct hit—could unleash dangerous shaking, she says.

THE NATION’S LATEST defense R&D plan, for 2025 to 2029, includes an undisclosed amount of new support for scientists, including for work on asymmetric warfare technologies. Horbulin, who set the effort in motion, is pleased. NASU’s institutes “are moving in the right direction and playing a vital part now,” he said during an interview in his spacious office at NASU headquarters, which is festooned with mementos such as autographed photos of Ukrainian cosmonauts. Indeed, he believes “the war is a catalyst for reviving” Ukraine’s scientific potential, which had deteriorated steadily since the Soviet breakup.

Ukraine’s embrace of military R&D has squeezed already scant resources for basic research, however, especially in areas without a plausible defense connection such as astronomy, botany, and the humanities. “It’s a very painful point,” NRFU’s Polotska says. Scientists in those fields “are as poor as church mice now.”

A return to equilibrium will have to wait until after the war ends. “Most of our scientists understand that it’s necessary to keep on this path,” Zagorodny says. That means remaining at their lab benches, while knowing their institute or university could be the next target for a Geran. “We’re staying here, doing our research,” Iurzhenko says. “That’s how we are fighting for our liberty.” □

The battle for Ukraine’s geological wealth

In late June, Russian forces advanced in the Donetsk region of eastern Ukraine, seizing another few square kilometers of ground—and a significant deposit of lithium. The loss adds to a growing tally of Ukraine’s geological riches that have fallen into enemy hands. It is also one more blow to a landmark agreement that the United States and Ukraine had signed weeks earlier, enabling U.S. firms to gain access to the nation’s mineral wealth.

Under the 30 April deal, the U.S. and Ukraine pledged to establish an investment fund to rebuild Ukraine with revenues from mineral, oil, and natural gas projects. Ukraine will maintain ownership of its natural resources, while future U.S. military aid would be deemed a contribution to the fund matched by revenue from Ukraine’s mineral wealth. But with war raging, implementation largely must wait, says Anatolii Bulat, director of the M.S. Poliakov Institute of Geotechnical Mechanics (IGTM), which is tracking the fate of the country’s mineral deposits. Without lasting peace in Ukraine or a U.S. pledge to help defend

Ukraine’s global rank in mineral production (2021)

- 2 Gallium
- 6 Kaolin
- 6 Titanium
- 7 Iron
- 8 Graphite
- 8 Manganese
- 10 Zirconium
- 10 Uranium

Ukraine’s mineral assets, the security situation in the country will be too unstable for a long-term investment in a mine and its supporting infrastructure, the Center for Strategic and International Studies argued in a recent briefing. It noted that such projects take an average of 18 years to complete and can cost \$1 billion.

In the meantime, IGTM researchers are fine-tuning their inventories of critical minerals. The institute recently completed what Kateryna Babii, IGTM’s deputy director, calls the first comprehensive analysis of Ukraine’s strategic mineral resources, as well as the factors complicating extraction. Ukraine currently prohibits public release of statistics from its extractive industries. But through

2021, the nation ranked among the top 10 countries in production of iron ore, manganese, titanium, gallium, and uranium (see table, left). It also held Europe’s richest known deposits of lithium, an alkali metal in high demand globally for use in electric vehicle batteries. In a rare implementation of the U.S.-Ukraine agreement, the Ukrainian government last month opened the door to investment in the Dobra lithium ore deposit, 300 kilometers southeast of Kyiv.

However, with the capture of the Shevchenko lithium deposit in Donetsk, Russia now controls two of Ukraine’s four major deposits. It has also seized territory holding scarce elements such as niobium and tantalum, as well as Ukraine’s biggest mine—the Zaporizhzhya Iron Ore Plant—a salt mining complex in Soledar, and dozens of coal mines. Altogether, Russia has wrested about 700 mineral deposits—nearly one-third of Ukraine’s total.

Russia has even taken aim at IGTM itself. Three drone attacks in 3 years have destroyed several labs at the 300-strong institute, although the blasts happened at night and no staff were injured, Bulat says. Still, he remains bullish. The U.S.-Ukraine minerals agreement may for now be aspirational, he says, but it “could be a road map for postwar revival.” —R.S.



The Zavallievsky Graphite Mine is a candidate for the U.S.-Ukraine minerals agreement.